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Reconstruction of an Arson Fire Scene Using Experiment Techniques and Fire Dynamics Simulator (FDS) Program

Jen-Hao Chi, Han-Liang Chien and Lu-Tien Yuan

***Abstract*—**This study collected a number of fire debris samples at an arson fire to conduct a series of analytical tests in metallographic analysis, thermal analysis experiment, and then to identify the reason for this fire. Collecting PU foam samples which had caused fire to spread in this actual arson case, and conducted thermal analysis experiments at 5 ℃/min of heating rates to obtain approximately 5127.81 J/g of heat release at temperatures between 385 and 405 ℃ and other thermal reaction parameters. These experimental data of thermal analysis were treated as the input data of the Fire Dynamics Simulator (FDS) program for the reconstruction of the fire scene. These research findings can also promote relevant personnel's understanding of the harmful aspects of PU foam in order to prevent fires in the future.

***Index Terms*—**arson fire, metallographic analysis, thermal analysis experiment, PU foam, Fire Dynamics Simulator (FDS) program

I. Introduction

In recent years, arson attacks in every country have occurred repeatedly. For example, over the past week in the United Kingdom there were 2,100 arson attacks, resulting in two people being killed and 55 injured with a loss of £40 million [1]. Obviously, the disaster of arson incidents should not be ignored. Since the 1950s, the international community has started to focus on measures to prevent arson attacks, developing many experimental techniques to enhance capabilities for analysis of fire debris [2]. However, for fire investigators, the most important work is to compile various clues from the fire and to complete the reconstruction of the fire scene in order to determine the process of fire spread and growth [3]. Although after more than 10 years of development and update, the FDS computer program is already equipped with the ability to simulate different fire scenes and has been widely used [4], its operation process still requires the thermal reaction parameters of many items to be inputted for the computer simulation. Thus, inputting the correct thermal reaction parameters is important and critical to the fire scenario operation of this computer program.

This study is based on an arson attack which occurred around 2 am on June 12, 2012 in Dayuan Township, Taoyuan County, Taiwan. According to the results of the official fire investigation, this case involved someone igniting the PU foam of a refrigerator near the originating position of fire, as show in Figure 1, which resulted in the PU foam fire spreading rapidly outward. This study used PU foam as experimental material and utilized thermal analysis equipment to obtain its heat reaction data at 5 ℃/min of heating rates as input parameters for the FDS program for the reconstruction of the entire arson attack. As PU foam has been widely used in the refrigerator or freezer equipment of families, supermarkets, factories, the findings of thermal reaction parameters in this study, in addition to being applied to the investigation tasks of other fire cases, can also promote users' awareness of the harmful aspects of PU foam as well as prevent the recurrence of other fires and ensure the security of human life and property.

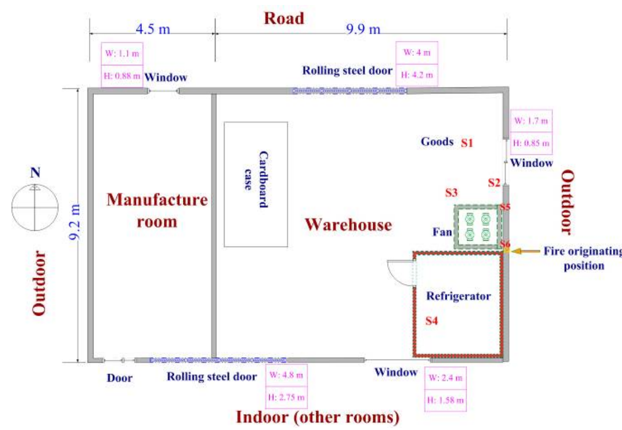

Fig. 1 Layout of the warehouse area behind the factory.

II. Experiment and Results

A. Metallographic analysis

The factory staff indicated that power to the fan and refrigerator near the ignition position was shut down when the fire broke out. However, the site investigation found that one of the fan power wires presented a molten mark phenomenon, where the rest of the wires showed no such condition, only partial burning on the outer layer of insulation. Therefore, this study cut above the molten mark wire as sample and put it into the extraction fluid, and then

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implemented grinding and polishing through twin variable speed grinder-polishers (BUEHLER, ISOMET 1000) to conduct a series of metallographic analysis tests. After that, a 1000 X microscope was used to observe the characteristics of the sample (see Figure 2) and compared its microstructure with that of short-circuited molten marks in the reference [4]. Figure 2 demonstrates that there are too many bubbles in a columnar-like shape. According to [5], the sample in Figure 2 is identified as not a primary molten mark caused by a short circuit in a powered-up state, instead, it was a secondary molten mark caused by a high temperature stream extending from another fire place. Therefore, based on factory staff and firemen's accounts, that there was no other electrical equipment near the fire place and the entire power supply to the factory was turned off, an electrical short circuit should be excluded as a cause of fire.

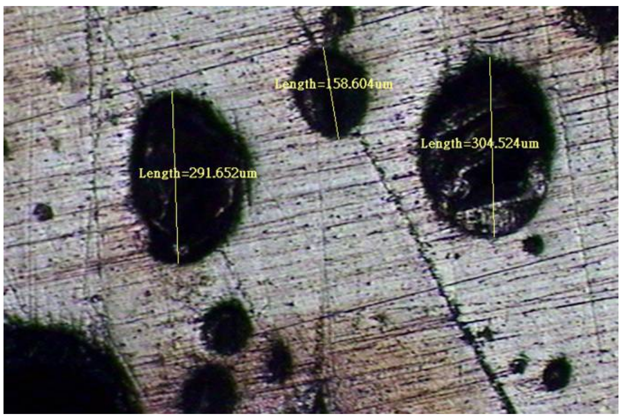
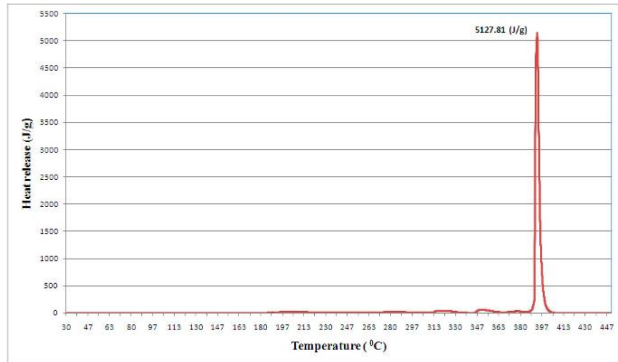


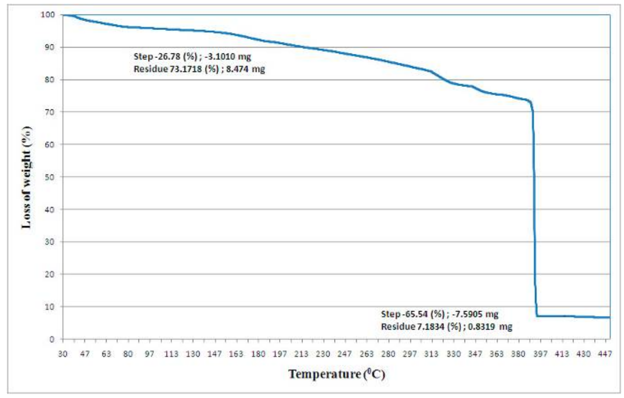
Fig. 2 Microstructure's image of Specimen consisting by metallographic analysis test (1000 ×).

B. Thermal analysis experiments

Owing to the fact that the main structure of the clean panel of the refrigerator near the ignition position was seriously burned, in order to understand the combustion behavior of the panel, this study found unburned clean panel samples in the second floor. Both sides of the panel are stainless steel, 1.2 mm thick, with a 50 mm thickness of PU foam in the middle. In this study, thermal analysis experiments were performed on a Mettler Toledo STARe system, TGA/DSC1-SF. Heating rate chosen for the temperature-programmed ramp was 5 ℃/min, to maintain better thermal equilibrium. The tests were conducted between 30–450°C with the sample of 11.58 mg PU foam to explore its per gram of heat release, as shown in Figure 3 (a). The results of the loss of weight in Figure 3 (b) demonstrate that PU foam started to decompose at a temperature of about 40 ℃ and the decomposition began to accelerate at a temperature of 120 ℃ (the slope of the curve becomes steeper). Therefore, when the temperature of the external fire source exceeds 120 ℃, the PU foam in the middle of clean panels can very easily burst into flames. The results of Figure 3 (a) and (b) show that, when being heated to around 395 ° C, the PU foam releases a large amount of heat at about 5127.81 (J/g), and after that, only approximately 7.2% of the ashes remain. Therefore, the PU foam between the clean panels in this fire case is regarded as highly flammable material.



(a) per gram of heat release



(b) loss of weight

Fig. 3 Test's results of PU foam by thermal analysis experiment within 5 ℃ /min.

III. COMPUTER SIMULATION ANALYSIS

A. FDS program introduction

The FDS computer simulation program was developed by the U.S. National Institute of Standards and Technology (NIST) [6]. It was first released to the public in February 2000 and is still in continuous improvement. FDS is a Computational Fluid Dynamics (CFD) software using Field Model to simulate different fire scenes [7]. This program has been internationally recognized and used widely [8-9]. The present study adopted the latest FDS version, 5.5.3, issued in June 2010 as a simulation tool. Relevant outcomes are described later in this paper.

B. Grid analysis and data model

In the calculation process of FDS computer simulation, if the grid is set too large, the accuracy of the entire fire simulation may be insufficient; conversely, if the grid is set too small, performing the simulation will consume too much computer memory. Therefore, this study referred to literature [10] using formula (1) to conduct the grid analysis as follows:

$$D^* = \left(\frac{Q}{\rho_\infty \cdot C_P \cdot T_\infty \cdot \sqrt{g}}\right)^{\frac{2}{5}} = \left(\frac{Q}{\rho_0 \cdot \frac{T_0}{T_\infty} \cdot C_P \cdot T_\infty \cdot \sqrt{g}}\right)^{\frac{2}{5}} = \left(\frac{Q}{\rho_0 \cdot T_0 \cdot C_P \cdot \sqrt{g}}\right)^{\frac{2}{5}} \quad (1)$$

Where Q is the heat release rate. According to NIST of heating PU foam by Core Calorimetry, the maximum heat release rate of PU foam after being heated for about 180

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seconds will reach 1,000 kW [11], therefore, the Q in this study is set at 1,000 kW. Air density (ρ0) is equal to 1.2 kg/m3; specific heat (Cp) is 1.0; starting temperature (T0) is set at 300 K.

Bringing the above data into formula (1) as follows:

$$D^* = \left(\frac{Q}{\rho_0 \cdot T_0 \cdot C_P \cdot \sqrt{g}}\right)^{\frac{2}{5}} = \left(\frac{1{,}000}{1.2 \cdot 300 \cdot 1.0 \cdot \sqrt{9.81}}\right)^{\frac{2}{5}} = 0.953$$

After repeating several simulation tests, this research intended to adopt 0.1 as the grid size, therefore, the formula (2) is as follows:

$$\frac{D^*}{\delta x} = \frac{0.953}{0.1} = 9.53 \qquad (2)$$

As the ratio of 9.53 is within the range of 4 to 16, according to results in the literature [12], a 0.1 m grid size should be acceptable.

As the main damaged area was the warehouse behind the factory (see Figure 1) and other spaces were only slightly smoked, the numerical model constructed by the computer program was thus limited to the area of the warehouse without including the other spaces. The numerical model of the warehouse in this study was first constructed from the first floor with a simulation area as follows: X-axis from 0 to 14.4m, Y-axis from 0 to 9.2 m and Z-axis from 0 to 4.2m. The simulation region of the second floor is as follows: X-axis from 0 to 14.4m, Y-axis from 0 to 9.2 m and Z-axis is 4.2 to 9.0 m. Based on the above-mentioned grid analysis, and using 0.1 m × 0.1 m × 0.1 m for the grid size, the total number of grids throughout the simulation area are 1,192,320.

C. *Material properties*

Before operating the FDS ver. 5.5.3 program, nine material properties data must be input. Four data, the thickness, specific heat, density, and thermal conductivity were obtained from the PU foam experiments, as shown in Table 1. The heat of combustion, reference temperature, pyrolysis range, heating rate after thermal decomposition shown in Table 1 were results obtained from previous thermal analysis experiments. In addition, the source of data about the heat of combustion was the FDS ver. 4.05 databases, as shown in Table 1.

TABLE I
MATERIAL PROPERTIES OF THE PU FOAM USED IN FDS PROGRAM SIMULATION

Material properties	Results of thermal analysis test
Thickness (m)	0.05
Specific heat (W-s/gm)	1.076
Density (kg/m3)	45
Conductivity (W/m℃)	0.016
Heat of reaction (J/g)	5,127.81
Heat of combustion (J/g)	30,000 [a]
Reference temperature(℃)	395
Pyrolysis rang(℃)	20
Heating rate(℃/min)	5

[a] Datebase of FDS ver. 4.05

D. *Simulation results and analysis*

This study used various objects in Figure 5 to construct a numerical model in the FDS program in accordance with the official fire investigation report, and set the heat release rate per unit size and simulated ignition time of the PU foam near the origin of fire as 900 kW/m^2 [13] and 600 seconds, in accordance with the experimental data on per unit area of the heat release rate of PU of the U.S. NIST. Then, material properties of three heating rates shown in Table 1 were entered into the FDS program to simulate the fire scenes. Comparing previous simulation results with on-site fire smoke traces will result in a computer simulation scene which is closer to the fire scene as well as having higher credibility. The smoke layer height of the eastern (the origin of fire), western, southern and northern sides of the numeric model under the condition of 5℃/min heating rate after the aforementioned verification, indicating that the results of computer simulations are very close to the height of smoke on the four sides walls at the fire site.

Thus, as shown in Figure 4, this study summarized the aforementioned research results to reconstruct the fire scene using the FDS program.

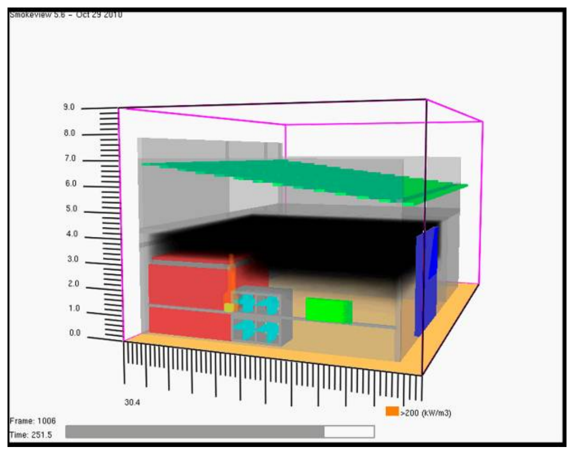

Fig. 4 Fire and Smoke spread profile of simulation.

IV. DISCUSSIONS AND RECOMMENDATIONS

PU foam with a thermal conductivity of only 0.016 W/m°C (see Table 1) is currently being commonly used as a good insulation material in many households and in industrial equipment. However, after conducting thermal analysis experiments on PU foam material at heating rates, it was found that, after being heated to a temperature 40 ℃, the PU foam started to exhibit a thermal decomposition reaction. When the temperature reached 120℃, the reaction began to accelerate, and when the temperature reached between 385□ and 405□, the released heat of combustion was up to 5127.81 J/g. After the reference literature [14-15] was studied, it was found that the thermal reaction data for the above-mentioned PU foam were even higher than those for many ignitable liquids which have caused many major fire or bombing incidents resulting in serious casualties and losses. Thus, once ignited, PU foam is not only a flammable material but will also release a great deal of combustion heat to lead the fire to grow and spread rapidly. Therefore, PU foam may not only be a good instrument for an arsonist but also a good ignitable accelerant in general households. To prevent a serious fire incident, the general user must be aware of its properties and ensure PU foam is not exposed to high temperatures.

Currently, the FDS program is widely used internationally, and many fire safety engineers use it to carry out quantitative assessments of fire effects for fire protection facilities and equipment within buildings in order to improve a building's fire safety strategies [16]. In addition, many fire investigation experts apply the FDS program to rebuild a fire scene for reviewing the casualties and fire rescue improvement measures or for the assessment of fire-related allocation of responsibilities as well as to provide an important legal document for criminal activity [17]. Before using it, fire investigators should pay more attention to the combustion experimental data of each item listed on the U.S. NIST website. They must also focus on debris at the fire scene, using relevant experimental equipment, and obtain data of material properties required by the FDS program in order to completely reconstruct the fire scene and ensure the impartiality and objectivity of the fire investigation results.

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